ANTIREFLECTION COATING DESIGN FOR MULTI-JUNCTION, SERIES INTERCONNECTED SOLAR CELLS

Daniel J. Aiken
Sandia National Laboratories*
Albuquerque, NM, 87185

ABSTRACT

Analytical expressions used to optimize AR coatings for single junction solar cells are extended for use in monolithic, series interconnnected multi-junction solar cell AR coating design. The result is an analytical expression which relates the solar cell performance (through J_{SC}) directly to the AR coating design through the device reflectance. It is also illustrated how AR coating design be used to provide an additional degree of freedom for current matching multi-junction devices.

INTRODUCTION

Proper antireflection (AR) coating design for monolithic series interconnected solar cells will become more important and challenging as the number of junctions increases. These devices will require an increasingly broad spectrum AR coating while also maintaining current matching for all subcells. The goal in designing antireflection coatings for series interconnected multi-junction solar cells is not only to couple the maximum amount of light into the device, but also to distribute that light to each subcell such that the device is as closely current matched as possible. . A formal procedure for designing AR coatings for these multi-junctions is necessary. This can be accomplished by extending the analytical expressions often used in single junction AR coating design to be applicable to multi-junction design. Antireflection coating design can then be used in conjunction with subcell thickness adjustments to provide a greater flexibility for achieving current matching.

SINGLE JUNCTION AR COATING DESIGN

The goal in developing high performance antireflection (AR) coatings for solar cells is to maximize the light generated current. An expression coupling the short circuit current of a single junction solar cell to the total device reflectance R(λ) is given by

$$J_{SC} = q\int_{\lambda} F(\lambda)\cdot EQE(\lambda)\,d\lambda = q\int_{\lambda} F(\lambda)\cdot IQE(\lambda)\cdot[1-R(\lambda)]\,d\lambda\,, \tag{1}$$

where F(λ) is the photon flux. This is the expression often used to calculate an integrated current in terms of the measurable parameters on the right side of Equation 1. Equation 1 can also be used to design an optimum AR coating because it directly relates J_{SC} to the AR coating design through the parameter R(λ).

Another convenient parameter used in AR coating design is the solar weighted reflectance (SWR) [1], defined as

---

* Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Department of Energy under contract DE-AC04-94AL85000.

This work was supported by non-Department of Energy funds.

$$SWR = \frac{\textbf{useable photons reflected}}{\textbf{total useable photons}} = \frac{\int F(\lambda)\cdot IQE(\lambda)\cdot R(\lambda)\cdot d\lambda}{\int F(\lambda)\cdot IQE(\lambda)\cdot d\lambda}. \tag{2}$$

Equation 1 can be manipulated and inserted into Equation 2, resulting in an alternative expression for SWR given by [2]

$$SWR = 1 - \left(\frac{J_{SC}}{J_{SC}\big|_{R(\lambda)=0}} \right) \tag{3}$$

Minimizing the SWR will minimize the number of reflected photons that would otherwise generate electrons which are then also collected. Minimizing SWR therefore couples the maximum amount of useable light into the solar cell and maximizes the short circuit current, as suggested by Equation 3. These equations assume negligible parasitic absorption in the antireflection coating.

MULTI-JUNCTION AR COATING DESIGN

Maximizing the light generated current in series interconnected multi-junction solar cells places an additional design requirement on AR coatings. In this case the goal is not only to couple the maximum amount of light into the device, but also to distribute that light to each subcell such that the device is as closely current matched as possible. Stated alternatively, the goal is to maximize the light generated current of the current-limiting subcell.

Equations 1 or 2 could also be used to design AR coatings for series connected multi-junction solar cells, provided that the term IQE(λ) is replaced with $IQE_x(\lambda)$. Here $IQE_x(\lambda)$ is the internal quantum efficiency of the current limiting subcell as measured using the spectrally selective light biasing technique described by Burdick and Glatfelter [3]. The problem in doing this is that, in searching for an AR coating design that minimizes the SWR, R(λ) will change which may also result in a different subcell limiting the current, especially if the subcells are already closely current matched before AR coating deposition. To eliminate this difficulty, Equation 1 can be modified to accommodate multi-junction AR coating design such that the correct current limiting subcell for any given AR coating design does not have to be explicitly known. A more general form of Equation 1 which is applicable to multijunction AR coating design is then given by

$$J_{SC} = \mathrm{MIN}\left[J_{SC1}, J_{SC2}, etc.\right] = \mathrm{MIN}\left[q\int_{\lambda} F(\lambda)\cdot IQE_1(\lambda)\cdot[1-R(\lambda)]d\lambda \;\; , \;\; q\int_{\lambda} F(\lambda)\cdot IQE_2(\lambda)\cdot[1-R(\lambda)]d\lambda \;\; , \;\; \text{etc.} \right], \tag{4}$$

where J_{SC1} and J_{SC2} are the short circuit currents that subcells 1 and 2 are capable of generating, respectively. Although the solar weighted reflectance is a useful parameter for designing and comparing AR coatings for single junction solar cells, this parameter loses its physical significance for multi-junction solar cells and is therefore not defined here. The difficulty is that a different subcell may be limiting the device in the two cases R(λ) = 0 and R(λ) ≠ 0, resulting in a SWR greater than unity.

Equation 4 is employed in practice by using optical theory [4] to model and calculate R(λ) as a function of the thicknesses and optical properties of the materials used in a given AR coating structure. These equations will accurately optimize the AR coating as long as the reflectance of the multi-junction cell structure can be accurately modeled. This requires knowledge of the index of refraction and absorption coefficients for all relevant cell materials. Additionally, because multi-junction cell structures are optically very complicated, analytic expressions for R(λ) quickly become unmanageable and computer simulation must be used. For example, all AR coating optimization reported here was done using FILM-STAR DESIGN optical thin film software from FTG Associates [5].

AR COATING DESIGN AS A CURRENT MATCHING TECHNIQUE

Multi-junction subcells that are already well current matched before AR coating deposition require a reflectance that is as low and flat as possible across the spectral range of interest such that current matching is maintained. The primary technique for current matching a multi-junction solar cell is by adjusting the individual subcell thicknesses. This technique is not infinitely flexible because the absorption in any subcell is dependent not only on its own thickness but also on the thickness of all subcells above it. Furthermore, increasing a subcells thickness to values significantly greater than the base diffusion length will not enhance that subcell's current generating capability. This imposes an upper limit on the useful thickness of any subcell in terms of current matching.

Proper AR coating design can provide an additional degree of freedom for current matching multi-junction devices by minimizing the reflectance in spectral regions where the corresponding subcells are current limiting the device, and trading that for higher reflectivity where other subcells have current to spare. Equation 4 will automatically perform this task by optimizing the AR coating design so as to maximize the current generating capability of the current limiting subcell.

This technique is illustrated with Figures 1 and 2. Shown in Figure 1 are the individual IQE curves of a typical 2-junction InGaP/GaAs multi-junction that is well current matched. Also shown is the modeled reflectance of a simplified cell structure with double layer AR coating that was optimized using Equation 4. It is apparent that the AR coating has been properly optimized such that reflectance loss is divided equally between both subcells, thereby keeping the multi-junction current matched.

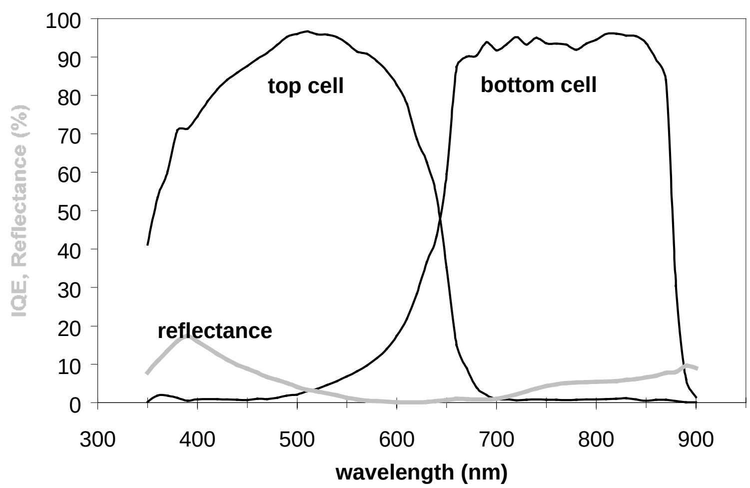

Figure 1 Reflectance of a 2-junction solar cell with an AR coating optimized for current matched subcells.

In Figure 2 a current mismatch scenario has been modeled by lowering the IQE of the top subcell. The AR coating optimized for this case has traded higher reflectance in the bottom cell spectral region for lower reflectance in the top cell region, thereby assisting in current matching this multi-junction. Table 1 lists the simulated short circuit current densities for the devices in Figures 1 and 2. The optimized AR coating for the current matched subcells of Figure 1 has resulted in both subcells possessing equal current loss due to reflection. This results in a maximum Jsc for the multi-junction. The optimized AR coating for the top subcell limited multi-junction of Figure 2 has traded higher reflectivity for the bottom subcell in exchange for low reflectivity for the current limiting top subcell. This results in a lower current lost due to reflection for the top subcell (0.48 mA/cm^2) and maximizes the multi-junction Jsc.

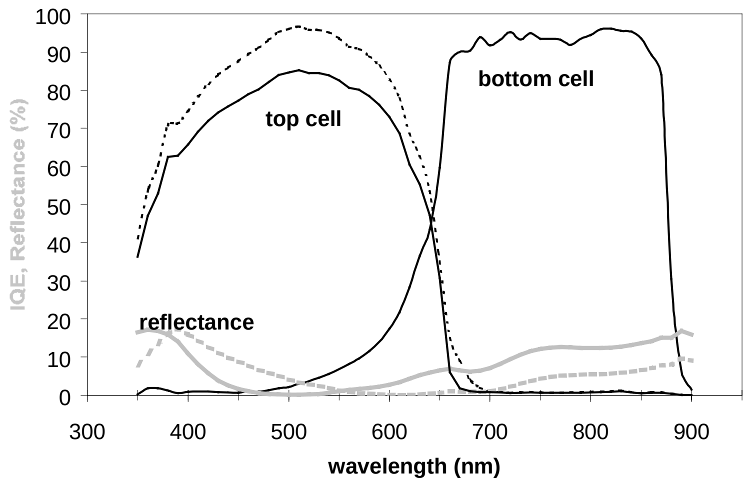

Figure 2 Reflectance of a 2-junction solar cell with an AR coating optimized for a current limiting top subcell. The top cell IQE and optimized reflectance from Figure 1 are shown as dashed lines for comparison.

Table I Simulated short circuit current densities for the 2-junction solar cells in Figures 1 and 2.

	Current matched (Figure 1)			Current mismatched (Figure 2)	
	Top cell	Bottom cell		Top cell	Bottom cell
Jsc (R(λ)=0), (mA/cm^2)	17.95	18.05		15.68	18.05
Jsc, (mA/cm^2)	17.22	17.22		15.20	16.39
Jsc lost to reflectance, (mA/cm^2)	0.73	0.83		0.48	1.66

Figure 3 illustrates the current matching technique for a hypothetical 4-junction solar cell with bandgaps chosen such that the multi-junction is nearly current matched. Shown in Figure 3 is the portion of the AM0 spectrum that each subcell could convert to current. The area under each curve is the current available to each subcell. In the limiting case of no reflectance loss this multi-junction is current limited by subcell 3, as suggested by Table II. This multi-junction is likely to be more difficult to current match by adjusting subcell thicknesses due to the larger number of subcells and the limited flexibility afforded by changing subcell thicknesses as discussed previously. The AR coating which optimizes this multi-junction performance is also shown in Figure 3. Current matching has been assisted by minimizing the current that subcell 3 has lost to reflection, as shown in Table II.

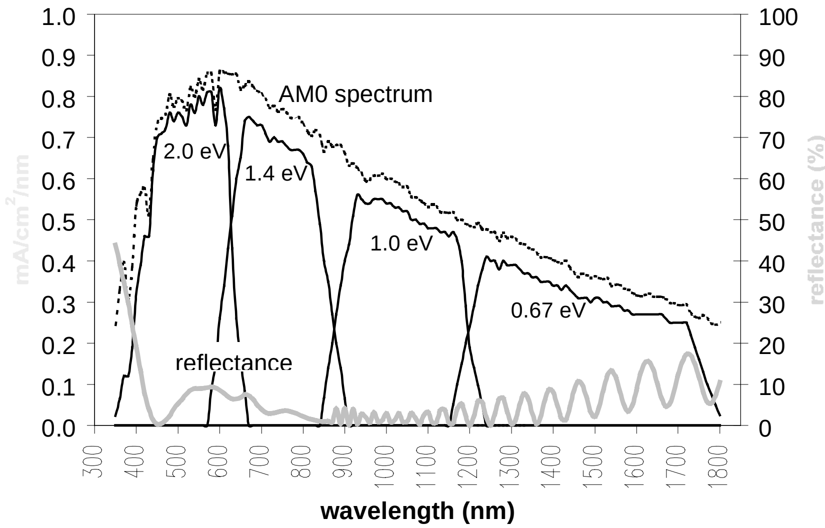

Figure 3 Reflectance of a simulated future 4-junction solar cell with an AR coating optimized for a current limiting third subcell.

Table II Simulated short circuit current densities for the 4-junction solar cell simulated in Figure 3.

	Top cell	2nd cell	3rd cell	Bottom cell
Jsc ($R(\lambda)$=0), (mA/cm^2)	17.31	17.34	16.30	18.29
Jsc, (mA/cm^2)	16.03	16.64	15.97	17.09
Jsc lost to reflectance, (mA/cm^2)	1.28	0.70	0.33	1.20

CONCLUSIONS

Analytical expressions exist for designing and optimizing AR coatings for single junction solar cells. In the single junction case the goal is to couple the maximum amount of light into the cell. For series connected multi-junction devices current matching is also a critical design goal. The goal in designing antireflection (AR) coatings for series interconnected multi-junction solar cells is therefore not only to couple the maximum amount of light into the device, but also to distribute that light to each subcell such that the device is as closely current matched as possible. Analytical expressions used to optimize AR coatings for single junction solar cells have been extended for use in monolithic, series interconnnected multi-junction solar cell AR coating design. The result is an analytical expression which couples the solar cell performance (through J_{SC}) directly to the AR coating design through the device reflectance. This expression assumes that the reflectance of a multi-junction device structure can be accurately modeled and therefore requires knowledge of optical constants for all relevant materials in the multi-junction. It was also illustrated how this expression can be employed such that AR coating design can be used to provide an additional degree of freedom for current matching multi-junction devices.

REFERENCES

[1] P. Doshi, G.E. Jellison, and A. Rohatgi, “Characterization and Optimization of Absorbing Plasma-Enhanced Chemical Vapor Deposition Deposited Antireflection Coatings for Silicon Photovoltaics”, *Applied Optics*, vol 36, no. 30, p. 7826, 1997.

[2] J. Zhao and M.A. Green, "Optimized Antireflection Coatings for High Efficiency Silicon Solar Cells*", IEEE Transactions on Electron Devices*, vol. 38, no. 8, p.1925, 1991.

[3] J. Burdick and T. Glatfelter, "Spectral Response and I-V Measurements of Tandem Amorphous Silicon Alloy Solar Cells", *Solar Cells*, vol. 18, p. 301, 1986.

[4] H.A. MacLeod, *Thin Film Optical Filters*, McGraw-Hill, 1989.

[5] version 2.0 from FTG Software Associates, P.O. Box 579, Princeton, N.J. 08542.